



Title: The evolution of sports nutrition and its application to human performance

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The evolution of sports nutrition and its application to human performance.

John Brewer

2014

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy by Publications



DECLARATION

I declare that this thesis is my own unaided work. It is being submitted for the degree of PhD by Publications at the University of Bedfordshire.

It has not been submitted before for any degree or examination in any other University.

A handwritten signature in dark ink, appearing to read 'John Brewer', with a stylized, cursive script.

Name of candidate: John Brewer Signature:

Date: 23rd September 2014

Acknowledgements

The late Sir Bobby Robson, and Mr Charles Hughes, offered me my first job as Head of Human Performance for the Football Association, ending my time as a post-graduate research student before sufficient data had been collected for a PhD. However without this position, I would not have embarked on my career in applied sport and exercise science, and I am grateful for the opportunity that they presented to me, and for a further 18 years spent at Lilleshall National Sports Centre.

Throughout my career, one person has remained as an advisor, mentor and friend: Clyde Williams, Emeritus Professor at Loughborough University has had a unique influence on the global development of sport and exercise science, and his support and motivation have been valued and respected since he offered me the chance to become a post-graduate student.

I would also like to acknowledge the opportunity that the University of Bedfordshire, and the then Vice Chancellor, Professor Les Ebdon, gave to me by offering me the chance to leave GlaxoSmithKline, to become a Professor of Sport. It is unusual for anyone to move from industry into academia, and I hope that the university feel that the appointment was as successful as I do.

Grateful thanks must also go to my supervisor and friend, Dr Paul Castle, whose guidance, advice, corrections and ideas have helped to bring this thesis to fruition.

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Abstract

This thesis summarises a series of academic publications that make a contribution to the field of sports nutrition over a period of 30 years. It begins with research in the field of carbohydrate and endurance sport reflecting the early era of research into carbohydrate and endurance performance, and evolves into studies investigating the impact of sports nutrition and hydration on team sports. It presents papers and other peer reviewed outputs that focus on the application of scientific knowledge to enhance human performance, whilst demonstrating the increasing awareness of the relative importance of carbohydrate and hydration in a range of both female and male team and individual sports. The thesis also highlights the challenge faced by the manufacturers of sports nutrition products in making use of advances in science to develop new and innovative products. The thematic nature of this thesis shows how sports nutrition continues to evolve. As science identifies new and legal means of enhancing human performance, so sport, athletes and coaches will demand more advanced and specialised approaches to refuelling and hydration. This thesis draws together findings from a series of publications which demonstrate how scientists, coaches, athletes and sports nutrition manufacturers need to work closely together to research, identify and interpret the next stages in an exciting and demanding area of research. It also reflects the scientific advancement in the field of sports nutrition over a thirty year period, identifies possible areas for future research, and the continued application of hydration and nutrition strategies to enhance male and female endurance and team sports.

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1.1 Introduction

1.1.1 Background

The peer reviewed papers, book and book chapters submitted within this thesis have been published over 30 years, between 1984, and 2014. They reflect a career in research and industry that has been closely aligned to the support of elite and recreational athletes, as well as research and product development. The consistent theme through the publications is the advancement in understanding of the metabolic and nutritional demands of sport, and the subsequent interpretation of knowledge to better inform elite and recreational athletes. The publications are listed in chronological order, but within the thesis they are reviewed and discussed thematically.

1.1.2 Location and date of the published work.

Papers published prior to 1992 resulted from research at the Sport and Exercise Science Department of Loughborough University. The papers and book chapters published between 1993 and 2004 were based on research from the Lilleshall Sports Injury and Human Performance Centre, the largest independent sport science centre in the UK, providing applied sports nutrition and sports science support to a wide range of National Governing Bodies of sport, professional teams and individual athletes. All publications subsequent to 2004 were published whilst at the University of Bedfordshire, although some of the knowledge and insight was obtained whilst Director of Sports Science for GlaxoSmithKline plc between 2004 and 2009

1.1.3 Thesis Structure

Section 3 of this thesis provides background into the development and evolution of sports nutrition, and advances in science that resulted in educational support for both elite and recreational athletes. It also reflects the growth of a sports nutrition and hydration industry that has developed as a result of advances in science. The section highlights some of the key studies during that time, and the context in which the submitted publications have occurred during this period.

Section 4 summaries each publication, and the contribution that has been made to our understanding of the field of sports nutrition and hydration.

2.1 Publications submitted in this thesis:

Peer reviewed papers

Publication 1

Williams, C., Patton, A. and Brewer, J. (1984) The metabolic challenge of the marathon. British Journal of Sports Medicine 18(4): 244-52

Publication 2

Brewer, J., Williams C. and Patton A. (1988) The influence of high carbohydrate diets on endurance running performance. European Journal of Applied Physiology. 57(6): 698-706

Publication 3

Williams, C., Brewer, J. and Walker, M. (1992) The effect of a high carbohydrate diet during a 30km treadmill time trial. European Journal of Applied Physiology 65(1): 18-24.

Publication 4

Davis J.A. and Brewer J. (1993) Applied physiology of female soccer players. Sports Medicine. 16(3): 180-189

Publication 5

Brewer, J. (1994) Nutritional aspects of women's soccer. Journal of Sports Science. 12 Special No: S35-38

Publication 6

Brewer J (2011) Low calorie sweetness and hydration: applications in exercise and sport.
Journal of the Agro Food Industry. 22(5) 35-38

Publication 7

Brewer J. and Warren L. (2014) A review of the potential implications of hot and humid
environmental conditions on soccer match-play performance. International Journal of
Sciences: Basic and Applied Research Vol 15(1) 584-589

Publication 8

Consensus Statement: Oral Health and Elite Sport Performance, British Journal of Sports
Medicine 2014

Book Chapters.

Publication 9

Brewer, J; The Female Player. (1994) In: Football (Soccer). Ed. B Ekblom, Pubs:
International Olympic Committee Medical Commission

Publication 10

Nutrition for team sports (1995). In: Sports Nutrition for Women. Authors: Bean, A., and
Wellington, P. Pubs A&C Black, London

Book

Publication 11

Brewer, J. London 2012 Official Guide: Athletics – Track Events, Carlton Books. Published
2011. ISBN 9781847326980

3.1 The evolution of sports nutrition and the context of the published work.

This section charts the evolution of sports nutrition that forms the basis of this thesis, reviewing a small number of key papers, and highlighting the context of the presented publications. Inevitably, since these cover a 30 year period, it is not possible to review a large number of papers, many of which have been reviewed within the submitted publications.

3.1.1 Early history

One of the first studies to identify a link between carbohydrate intake and endurance capacity was by Christensen and Hansen (1939), who placed subjects on 3-7 days of either a high fat-protein diet, or a high carbohydrate diet. After the latter, they found that the capacity for endurance exercise at 70% of VO_2 max on a cycle ergometer increased by approximately 300%. They also found that exhaustion coincided with low levels of blood glucose, suggesting a link between endurance capacity (the length of time that exercise could be sustained before exhaustion), and hypoglycaemia.

As a result of this study, attention focussed on the link between fatigue and low levels of liver glycogen. However the development of the needle biopsy technique for the analysis of muscle tissue in the 1960's revealed that there was greater reliance on muscle glycogen, highlighted by Bergstrom and Hultman (1966), who examined changes in muscle glycogen after a regimen of exercise and diet. After exercising one leg to exhaustion on a cycle ergometer they found that muscle glycogen was depleted, and that exhaustive exercise, followed by a high carbohydrate diet, resulted in over-compensation of muscle

glycogen in the exercising leg only. In contrast the non-exercising leg showed no changes in muscle glycogen concentration. This study suggested that fatigue during endurance exercise and muscle glycogen concentration is closely related, and that a subsequent high carbohydrate diet could elevate muscle glycogen to a concentration exceeding normal resting values. A further study by Bergstrom et al (1967) measured the muscle glycogen content of the quadriceps femoris muscle of 9 subjects after they had followed exhaustive exercise with consumption of either high fat-protein, or high CHO diets. Whereas the high fat-protein diet resulted in muscle glycogen levels of only 0.6g/100g of muscle, the high CHO diet resulted in muscle glycogen levels of 4.7g/100g muscle. These diets were followed by further exhaustive exercise at 75% VO_2 max on a cycle ergometer, with mean exercise times of 59 mins for the fat-protein group, and 189 mins for the high-CHO group. Bergstrom et al (1967) concluded that muscle glycogen content could be varied by different diets, and that the pre-exercise muscle glycogen content had an impact on work capacity. Based on this and other similar studies, Astrand (1967) recommended a protocol of exhaustive exercise, a subsequent three day low carbohydrate diet, followed by a 3 day high carbohydrate diet, in order to over-compensate muscle glycogen stores and gain an improvement in endurance capacity. This protocol was widely adopted by endurance athletes, despite the research studies utilising cycle ergometry, rather than running, as an exercise modality. Furthermore, studies examining "endurance capacity" – the exercise time taken to reach exhaustion, can over-emphasise the potential improvement in "endurance performance" – the time taken to complete a set distance, which is a more valid measure of true performance in sport.

3.1.2 Carbohydrate and running.

One of the first studies to examine the impact of high carbohydrate diets on endurance running performance was that of Karlsson and Saltin (1971). Ten subjects completed a 30km race consuming either a normal mixed diet (40% CHO) or a high CHO diet (70% CHO). Six subjects performed the first trial after the high CHO diet, and four after the mixed diet, a procedure that was reversed for the second trial. All subjects produced their best times after the high CHO diet, with better maintenance of performance during the latter stages of the race. Furthermore, those showing the earliest fatigue had the lowest pre-race glycogen concentrations. Although Karlsson and Saltin (1971) concluded that high CHO diets could enhance endurance performance, closer examination of the data revealed some flaws in the study, since subjects were either elite or recreational runners, and the elite group combined their high CHO diet with an organised race, where incentives to perform well were high. This elite group consumed their normal diet prior to a time trial specifically organised for the study, and their times declined. It is therefore hard to determine whether the key influencing factor for these subjects was their diet, or the competitive 30km race.

In a further running study, Goforth et al (1980) found a 9% improvement in run time to exhaustion at 80% of VO_2 max after consumption of a high carbohydrate diet, consisting of 2 days consuming approximately 550g of CHO per day, and 3 days consuming 350g of CHO per day. When compared with a pre-exercise "normal" diet, Hall et al, (1983) found a 12.1% increase in endurance capacity when subjects ran at a constant speed on a treadmill ($3.9 \text{ m}\cdot\text{s}^{-1}$), after following the Astrand (1967) dietary regimen.

It was the paucity of the literature on carbohydrate consumption and running performance, and the need to best-inform practitioners at a time when endurance running was becoming increasingly popular, that resulted in the first three publications submitted in this thesis; Williams et al (1984), Brewer et al (1988) and Williams et al (1992). This work had significant impact on our understanding of the science, enhanced the information that was provided for athletes and coaches, and was funded by Mars Confectionery Ltd., who sponsored the London Marathon. The Williams et al (1984) paper examined the metabolic challenge of marathon running for elite and recreational runners, showing that regardless of ability, the 26.2 miles of a marathon places significant demands on the body's stores of liver and muscle glycogen. The paper uses laboratory data to speculate on the metabolic demands of marathon running, suggesting that manipulation of pre-marathon diets to increase CHO consumption, whilst running at a relative exercise intensity that enables fat stores to contribute to metabolism, is crucial for marathon success. In the subsequent study by Brewer et al (1988), three groups of subjects ran to exhaustion on a motorised treadmill at speeds equivalent to 70% of VO_2 max. Subjects consumed high-CHO (either complex or simple CHO), or normal mixed diets for three days, before repeating the run to exhaustion. The two high-CHO groups improved their run times by 23-26% on the second trial, whilst there was no significant difference in the second time of the mixed diet group. This was one of the first studies to demonstrate that endurance running capacity can be improved following consumption of a high-CHO diet. To investigate whether endurance running performance could be improved, and to replicate the Karlsson and Saltin (1971) paper under controlled laboratory conditions, the study in the Williams et al (1992) paper was undertaken. Two groups of subjects performed two 30km time trials on a motorised treadmill, 7 days apart. During the intervening period subjects consumed either a normal

mixed diet (40% CHO), or a high-CHO diet (60-70% CHO). Whilst there were no significant differences in final performance times for either group, the high-CHO group demonstrated significantly faster running speeds and lower fatigue during the last 10km of the second time trial. These data suggested that the magnitude of improvement in endurance performance is likely to be less than that seen in endurance capacity, and manifests as a lower rate of fatigue towards the end of a race. The results of these studies were disseminated to athletes by the London Marathon sponsor, and guided the educational material provided to marathon runners in the UK, helping to embed much of the thinking around the importance of high-CHO diets for marathon running.

3.1.3 Carbohydrate and team sports.

A role as Head of Sports Science for the Football Association highlighted the need to establish the efficacy of carbohydrate ingestion for team sports. In the late 1980's there was little, if any, recognition of the role that sports nutrition could play in team sports such as soccer, and frequently overt resistance to the use of hydration and nutrition strategies to enhance performance and training. Since much of the research at that time focussed on endurance sports, there was little scientific evidence to link the improvements that had been observed with endurance running, to team sport performance. Since team sports depend to a large extent on work rate, rather than endurance capacity, it was natural to extend the research outlined in Publication 3 of this thesis, and to ascertain whether there was a role for nutrition and hydration in enhancing performance in a sport such as soccer where work rate is critical. Whilst at the time it was relatively easy to quantify the demands of endurance sport, as exemplified in Publication 1, there was only limited knowledge of the physical and metabolic demands of team sports, and their possible implications for

nutrition and hydration. The need and desire to examine the demands and nutritional requirements of team sports resulted in the related theme of publications presented in this thesis.

One of the earliest studies to assess the physiological demands of soccer was that of Reilly and Thomas (1976), which found that players covered up to 10km during a 90min match, including approximately 100 sprints over an average distance of 15m. The publication of the Football Association's coaching manual by Hughes (1990), entitled "The Winning Formula" placed significant emphasis on physical fitness and sustained high intensity play throughout a game, and the importance of re-fuelling strategies. As a result, and in recognition of the need to highlight the role of sports nutrition in soccer performance, the Football Association requested a scientific appraisal of the physical demands of team sports, and whether these activities provide a metabolic challenge to players that could be influenced by the type of dietary manipulation used in endurance sports. Although Jacobs et al (1982) had established that the diets of soccer players were generally low in carbohydrate, few studies had established whether or not the physiological demands of team sports were sufficient to challenge the body's stores of energy and fluid. The publications presented in this thesis by Davis and Brewer (1993), and Brewer (1994¹), were as a consequence of this request from the Football Association. The Brewer (1994²) book chapter reviewing the demands of female soccer was invited by the Medical Commission of the International Olympic Committee (IOC), and published in the IOC Handbook of Sports Medicine and Science: Football (Soccer), (Ekblom, 1994). During the 1990's there was an increasing awareness of the role that nutrition plays in the support of sports which consist of intermittent, high intensity activity for a reasonably prolonged period

of time (greater than 60 minutes), although there is no definitive study or review paper which addresses this issue. It is suggested that this is partly due to the difficulty of assessing physical performance through dietary intervention strategies in a team sport environment, and hence the impact of nutrition on the physical performance of individuals performing team sports was, and remains, hard to determine. Whilst there were some studies evaluating the impact of nutritional interventions on specific team sports such as ice hockey (Burns and Duggan, 1994), Australian football (Schokman et al, 1999), and soccer (Rico-Sanz et al, 1998), there were few attempts to amalgamate the findings into a series of recommendations for team sport players and coaches. Hence the submitted peer reviewed book chapter, Nutrition for Team sports, (in Sports Nutrition for Women; Eds Bean and Wellington, 1995), was one of the first to provide a series of science based, nutritional recommendations for team sports.

Recently, the submitted Brewer and Warren (2014) paper, reviewed the impact of hot and humid conditions on soccer match-play performance. This paper was commissioned by a sponsor of the England Football team, and used to support and a high profile promotional campaign for the 2014 FIFA World Cup, focussing on hydration strategies for playing soccer in hot and humid conditions.

3.1.4 The role of Carbohydrate-Electrolyte solutions in fuel and fluid replacement.

Whilst much of the research during the 1980's and 1990's focussed on the role of nutrient consumption on performance, there were significant data and publications emerging to support the ingestion of carbohydrate in fluid form, in combination with water and electrolytes, as a means of providing both fuel and fluid to the exercising athlete. Studies indicating the metabolic (Maughan et al 1987) and performance (Maughan 1992) benefits

of carbohydrate-electrolyte solutions helped to drive the launch of commercial products designed to provide oral rehydration and refuelling. Nicholas et al, (1995), found that endurance running time to exhaustion increased by 33% following consumption of a carbohydrate-electrolyte solution. Whilst this study has subsequently been criticised for the interpretation of the data (Heneghan et al, 2012), it was used as a means of supporting the benefits of an isotonic drink, and an integral part of a high profile marketing campaign for many years.

Isotonic drinks have a carbohydrate content of between 4% and 8%, and contain electrolytes, normally sodium and potassium. The inclusion of carbohydrates and electrolytes to create an optimal concentration and osmolality has been shown to maximise the rate of gastric emptying, and subsequent absorption from the gut (Maughan et al, 1997). This provides a means of rapidly replacing the fluid, fuel and electrolytes that are lost during exercise, particularly in hot and humid environments when the thermoregulatory demand on the body is at its greatest. In many shorter duration events, rehydration becomes a greater priority than refuelling, since the demands of exercise are not sufficient to challenge stores of muscle glycogen. Consequently, hypotonic solutions, containing electrolytes but with a carbohydrate concentration of less than 4%, have been developed to optimise fluid intake, rather than to replace energy. These rehydration products have become popular amongst individuals who exercise to lose weight due to their lower calorific content. A palatable flavour is known to enhance the voluntary uptake of fluid during exercise (Minehan et al, 2002), and the challenge to retain a scientific formulation, optimising osmolality whilst retaining a flavour that encourages consumption, is one that has been faced when developing many isotonic and hypotonic products. Inclusion of

sodium is a particular challenge, since this is essential for a product's osmolality and electrolyte replacement, but creates a taste that is too salty for the user. One means of offsetting this is through the use of carbohydrate, but this can raise the concentration of a solution over the desired 4% and 8% limits, for hypotonic and isotonic solutions. Thus in order to retain the scientific integrity of a product, to enhance taste, and to reduce calorific content, artificial sweeteners (frequently aspartame) are used to regulate taste and carbohydrate levels. Whilst there has been considerable discussion about the potential link between aspartame consumption and cancer (Marinovich et al, 2013), the levels used in sports drinks remain well below the maximum daily consumption recommended by the Food Standards Agency of 40 milligrammes per kilogramme of body weight per day. The submitted paper (Brewer, 2011) is the only one of its kind to review the role of artificial sweeteners in hydration products, and followed an invitation to present on the topic at the Annual Conference of the International Sweeteners Association in Brussels in 2012. The consequent recognised expertise in the role that artificial sweeteners play in the manufacture of sports drinks, and regulation of sugar content, osmolality and taste, resulted in an invitation to contribute to the submitted Consensus Statement on Oral Healthcare and Elite Sport Performance, published in the British Journal of Sports Medicine, (Needleman et al, 2014). This paper reviews the impact of the acidity and sugar content of sports drinks on dental caries and erosion, and provides practical advice for athletes on optimising hydration and energy levels, whilst minimising the risk of damage to teeth.

3.1.5 Do sports drinks work? A review paper by Heneghan et al, 2012.

A review paper by Heneghan et al (2012) cast doubt on the quality and validity of many of the peer reviewed papers that have been used to develop new products, and support new claims, by the sports nutrition and hydration industry. It questioned the potential for bias in the selection of studies used by manufacturers seeking to make claims, and the way in which data had been interpreted. It also questioned the variability of many of the measures that were collected and reported, and the low sample size in some of the studies. However, the Heneghan et al (2012) paper failed to acknowledge the clear link between the metabolic demands of physical activity (which are known to deplete muscle glycogen stores and cause fluid to be lost), and the positive impact of replacing these through exogenous supplementation. It also failed to recognise that the differences between success and failure are often extremely small, hence the marginal differences that an effective hydration and refuelling strategy can have may have a large impact on the final outcome of a competition. Of equal concern was the claim by Heneghan et al (2012) that studies with fewer than 100 subjects are "small". In human experimentation in sport and exercise science, studies with appropriate blinding and cross over designs frequently use 10-20 subjects, and to suggest that these are not valid fails to acknowledge the rigour with which most peer reviewed studies are conducted, and the practical nature of human investigations. Finally, Heneghan et al (2012) claimed that many of the studies which have shaped current sport nutrition research and practice, were at a high risk of bias. However, closer examination shows that Heneghan et al (2012) used methods for assessing bias which were based on the methodology for large clinical trials, where conditions cannot be controlled in the same manner as laboratory experiments. The vast majority of the studies

that have shaped and contributed to the evolution of sports nutrition have been conducted in a tightly controlled manner including appropriate rigour, blinding and randomisation.

3.1.6 Summary

The publications submitted as part of this thesis support the overwhelming premise that effective refuelling and hydration has a large impact on improving performance in many sports, whilst recognising that there are other activities, (for example low intensity, short duration exercise) where a loss of fuel and fluid do not challenge performance. Today, manufacturers of sports drinks are unable to make any claims regarding the efficacy of their products unless the research has been approved by the Food Standards Agency (FSA).

The publications have made a contribution to the evolution of sports nutrition and the development of new products and claims over a period extending to almost 30 years. Studies that have been commissioned and overseen whilst at GlaxoSmithKline have also contributed to this area, along with a wealth of non-peer reviewed publications and communications aimed at educating and informing the general public. As an example of this, the submitted book, the "London 2012 Training Guide - Athletics (Track)", was written at the invitation of the London Organising Committee for the Olympic Games (LOCOG), and contains chapters on sports science, sports nutrition and hydration. It was one of a series of four sports-specific books commissioned by LOCOG for the London 2012 Olympic and Paralympic Games.

3.1.7 The future of sports nutrition?

In the last 30 years, the evolution of the science of sports nutrition, and its subsequent application to human performance, has had a transformative effect on performance, recovery and training. Carbohydrate and hydration are critical in meeting two of the biggest challenges of most forms of physical activity, namely the depletion of fuel stores, and the loss of fluid. It is unlikely that there will be such rapid advancement in knowledge in the next 30 years, but instead a refinement in understanding and application which will result in recommendations that are tailored to meet the specific needs of individuals, sports and environments.

Whilst the roles of carbohydrates and fluid are largely understood and established, the use of other supplements, that include creatine, caffeine, sodium bicarbonate, sodium phosphate, glutamine and amino acids all need further research. In particular, the use of combinations of supplements and ingredients, and their use at specific times or for specific need-states, requires further knowledge. Although we are beginning to understand the impact of, for example, combining protein with carbohydrate during recovery (Betts 2005) we still have very limited knowledge of the potential metabolic impact that could result from other combinations of ingredients.

The shift from generic recommendations, to those related to body mass or to an activity, is evolving, and better education of coaches, athletes and the manufacturers of sports nutrition products is needed to enhance understanding of the nature, volume and timing of nutritional intake. Whilst we know that carbohydrate is important in most endurance

activities, the need for carbohydrate in shorter duration activities (such as those under 90 minutes) may have been exaggerated, and this needs further exploration and explanation.

The potential for nutrition – and sports nutrition – to influence individual gene expression is an area that has recently become known as nutrigenomics. Research in this area will provide a better understanding of how nutrition can influence gene expression, and act at molecular level on the muscle cell. It is possible that the genetic predisposition of an individual will make them more prone, or resistant to, the effects of different food types. Advances in this area may make it possible to customise sports nutrition products for individuals, so that performance can be optimised.

The last 30 years has been a time of rapid advancement in sports nutrition and human performance. In sport, the difference between success and failure can often be measured in milliseconds or millimetres. Whilst it is uncertain what future advances in sports nutrition will unfold in the next 30 years, it is certain that whatever they are, if applied correctly they will play a large part in advancing sports performance, and could consequently make the vital difference between winning and losing.

4.0 A review of the submitted publications.

Publications 1, 2 and 3: Historical and commercial context.

From 1984 to 1988, the sponsor of the London Marathon was Mars Confectionary Ltd. To increase understanding of the role of nutrition in marathon running, they funded a series of research projects at Loughborough University. Together with the first three submitted publications, they resulted in raising awareness of the role of sports nutrition in endurance sport and were used by Mars to provide practical advice to competitors. The author was subsequently invited by Mars to present the findings of these studies to audiences at conferences in Russia (twice), Dubai (twice), Saudi Arabia (twice), Romania, Bulgaria, Slovenia, Greece and Lithuania.

4.1.1 Publication 1.

Williams, C., Patton, A. and Brewer, J. (1984) The metabolic challenge of the marathon.
British Journal of Sports Medicine 18(4): 244-52

Aim

To gain a better understanding of the metabolic and physiological demands of marathon running in elite and recreational runners, and the implications for training and nutrition.

Contribution to the advancement of knowledge

This paper was the first of its kind to assess the metabolic and physical demands faced by both recreational and elite runners when completing a marathon. It identified the differences in relative exercise intensity that exist between elite and recreational marathon

runners, and the energy intake that is required to sustain performance. In increasing the understanding of the demands of marathon running, it had an impact on the training and nutritional regimens that are required to support performance.

The paper contributed to an understanding of the energy and training requirements of marathon running. As such, it made a major contribution to both the understanding of the demands of the race, and the educational support that is provided for runners training and competing in marathons.

Findings

This paper combined a review of the existing literature on endurance performance, with a study relating laboratory data collected on ten elite and recreational runners to their performance in the 1984 London Marathon. It identified differences in VO_2 max between elite and recreation marathon runners ($70 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ vs $56 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ respectively), but also highlighted differences in the running economy of elite and recreational athletes, showing that elite runners tend to be more economical at a range of running speeds. The study found that elite marathon runners were able to sustain a pace that was equivalent to a blood lactic acid concentration of 2 mM , whereas recreational runners were only able to sustain a pace equivalent to 89% of their 2 mM lactic acid concentration. It was concluded that elite runners have both a higher absolute VO_2 max value, and are able to sustain higher relative exercise intensities (% of VO_2 max) during a race. The study suggested that training could improve marathon running performance by increasing the relative exercise intensity that could be sustained, rather than through an increase in VO_2 max. The paper demonstrated that individuals with a highly developed VO_2 max could still

improve endurance running performance, and as a result had an impact on training guidelines and in particular, training intensity.

Extrapolation of laboratory data used to calculate energy expenditure (using an estimate of the energy equivalent per litre of oxygen consumed during the race) indicated that the metabolic cost of running a marathon was approximately 2500 kcal (10.3 MJ) for elite and recreational runners. Whilst the total energy expenditure of elite and recreational runners was found to be similar, the rate of energy expenditure for the elite runners was higher. The total energy expenditure was similar to all athletes' daily energy intake, so in theory, when combined with energy reserves, completing the 26.2 mile marathon distance should not present a challenge to metabolism. However, the rate of energy metabolism required for both elite and recreational runners was shown to require a large contribution from the body's stores of glycogen, since the athletes were unable to metabolise fatty acids at the rate required. The paper suggested that a high carbohydrate diet was essential for marathon runners, and that carbohydrates were best consumed up to 3 hours before a race, to prevent an increase in insulin that may suppress metabolism of fatty acids (Costill et al, 1977). It suggested that training intensity needed to be sufficient to stimulate an increase in mitochondria density, and to increase VO_2 max and the relative exercise intensity that can be sustained. The findings of this paper still provide the foundations for much of the advice that is given to current recreational and elite marathon runners, emphasising:

- The role of high carbohydrate diets for runners of all abilities,

- The importance of developing the ability to sustain a high relative exercise intensity,
- The importance of a high VO_2 max value

4.1.2 Publication 2.

Brewer, J., Williams C. and Patton A. (1988) The influence of high carbohydrate diets on endurance running performance. *European Journal of Applied Physiology*. 57(6): 698-706

Aim

To determine whether dietary manipulation using simple and complex carbohydrate diets could enhance endurance running capacity (run time to exhaustion) at speeds equivalent to 70% of VO_2 max.

Contribution to the advancement of knowledge.

Publication 1 identified that there is a significant metabolic challenge for both elite and recreational marathon runners. This second study was the first laboratory study to investigate the impact of high (simple and complex) carbohydrate diets on endurance running capacity (run time to exhaustion). It was one of the first studies to show that running performance could be improved after consumption of a high carbohydrate diet, and the findings were used by the London Marathon sponsors to promote correct nutritional regimens for runners. The study provided strong evidence to suggest that muscle glycogen supercompensation occurred when carbohydrate diets were consumed after exhaustive running (as opposed to previous studies which had focussed on cycling).

Findings

Thirty subjects (15 male, 15 female) performed two runs to exhaustion at speeds equivalent to 70% VO_2 max on a motorised treadmill. After this they were randomly assigned to one of three groups that consumed either a high complex carbohydrate diet, a

high simple carbohydrate diet, or a control diet, for a three day recovery period. There were no differences in run time to exhaustion for all three groups during the first trial, these being 119.2 (± 19.5) mins, 105.9 (± 22.4) mins and 114.5 (± 15.6) mins for the Control, Complex CHO and Simple CHO groups respectively. The post-Trial 1 diet resulted in a 40% increase in energy intake for all three groups, but in the case of the two high carbohydrate groups, this was achieved with a 70% increase in carbohydrate intake. The energy intake increase for the Control group resulted from a deliberate increase in fat and protein intake, ensuring that the diets of all three groups were isocaloric.

Table 1: Run times for each group on Trial 1 and Trial 2

	Trial 1 (mins)	Trial 2 (mins)
Control	119.2 \pm 19.5	122.4 \pm 22.4
High-Complex CHO	105.9 \pm 24.4	133.3 \pm 46.5 *
High Simple-CHO	114.5 \pm 15.6	140.6 \pm 27.0 *

* Indicates a longer run time compared to Trial 1 ($P < 0.01$).

Table 1 shows that there was a significant increase in run time to exhaustion for the Complex and Simple CHO groups on trial 2, representing increases in endurance running capacity of 26% and 23%. However the Control group's Trial 2 run time of 122.4 mins was not significantly different to that of Trial 1.

Throughout Trial 2, both CHO groups exhibited significantly higher Respiratory Exchange Ratios, (RER), suggesting a higher contribution to metabolism from CHO from the outset. This was not evident in the Control Group. RER values over 0.85, and blood glucose levels over 4 mmol.l⁻¹, at the end of the Trial 2 for both CHO groups suggested that CHO

was still contributing to metabolism at exhaustion, and it was speculated that this might be due to fatigue occurring as a result of localised, (rather than complete), glycogen depletion in Type I muscle fibres, particularly since the constant treadmill speed prevented any change in running gait. Prior to Trial 2, both CHO groups demonstrated significantly lower plasma FFA concentrations when compared with pre-Trial 1 values, possibly due to elevations in insulin levels as a result of the high carbohydrate diets. However the improvements in performance suggested that despite the elevation in CHO metabolism from the outset of Trial 2, this was not sufficient to metabolise CHO at a rate which resulted in early glycogen depletion.

Although muscle biopsies were not taken, the study provided evidence to show that recovery from exhaustive running, and subsequent performance, could be enhanced following consumption of diets high in simple or complex CHO. The absence of a significant run time improvement in Trial 2 by the Control group, who consumed an isocaloric diet post-Trial 1, suggested that the observed improvements were due to the increase in CHO consumption, rather than an increase in energy intake.

The study demonstrated that improvements in run time to exhaustion, and post-exercise recovery, can be obtained with both complex (starch-based) and simple (sugar-based) carbohydrates. Many of the findings of this early study helped to lay the foundations for future research and education in the field of endurance nutrition. Today, carbohydrates are normally defined by their glycaemic index, (GI), with simple CHO foods tending to have a high GI, which can elevate plasma insulin and decrease plasma FFA, and as a consequence are recommended for post-exercise consumption. Lower GI foods are recommended pre-exercise, due to their reduced impact on insulin and fat metabolism, yet

both low and high GI carbohydrates are known to enhance performance. The GI-based messages that are now provided for athletes reflect much of the early work investigating simple and complex CHO - which includes this study - that helped to lay the foundations for research and education in sports nutrition.

4.1.3 Publication 3.

Williams, C., Brewer, J. and Walker, M. (1992) The effect of a high carbohydrate diet during a 30km treadmill time trial. *European Journal of Applied Physiology* 65(1): 18-24.

Aim

To determine whether running performance, as defined by time taken to complete a pre-determined race distance, could be improved following the consumption of a high carbohydrate diet.

Contribution to the advancement of knowledge

The previous paper identified that endurance capacity, could be extended by 22-26% after consumption of a high carbohydrate diet. This study examined the more sport-relevant measure of running performance – the time taken to complete a set distance - and was the first laboratory study to examine this in runners over a 30km distance. Whilst confirming that fatigue during the latter stages of an endurance race can be reduced after consumption of a high carbohydrate diet, the study highlighted the much smaller improvements in race performance that occur after CHO consumption, when compared with those observed in endurance capacity. This has helped to manage the expectations of runners who consuming pre-race carbohydrate, but has sometimes been overlooked both by manufacturers making claims (e.g. Lucozade Sport, "helps you go 33% longer"), and more recently by Heneghan et al, (2012), who suggested that there was no overt attempt on the part of scientists or manufacturers to raise awareness of this difference, despite this paper highlighting it almost 30 years ago. This study found that endurance performance over 30km could be improved by approximately 2% after a high CHO diet, or

2.6 mins. This seemingly small change is of huge significance to many runners, and could make the difference between a successful or non-successful race. For Heneghan et al (2012) to suggest that this is of little relevance, fails to understand the importance of small differences in time in competitive sport.

This was the first paper to simulate endurance racing conditions (running) in a laboratory, and as such it made a unique contribution to the understanding of the role of high carbohydrate diets within endurance running. Whilst the results did not conclusively show that high carbohydrate diets improved endurance performance, they did strongly suggest that this would be the case, through a reduction in fatigue during the latter stages of a race. It is likely that the magnitude of the performance improvement would have been greater over a longer distance, such as the 42km of a marathon, rather than the 30km used in this study. The study emphasised the relatively small margins of improvement in endurance performance that could be observed as a result of dietary manipulation, which are considerably less than those previously observed in endurance capacity.

Findings

Two groups of subjects completed two 30km time trials on a motorised treadmill at a self-selected pace, each separated by a period of 7 days. Treadmill speed was controlled by a hand-held device, and monitored by a computer with visual feedback for the subject. Subjects' diets were monitored for 3 days before Trial 1 by means of weighed food intake diaries. For the first three days post-Trial 1, subjects in the CHO group increased their CHO consumption by 70%, and energy intake by 50%. This increase in energy intake was replicated by the Control group, by increasing their intake of fat and protein. For the

remaining four days leading up to Trial 2, the CHO group increased CHO and energy intake by 35% and 24% respectively, when compared with their pre-Trial 1 diets. A similar increase in energy intake occurred for the Control group by increasing fat and protein intake, thus ensuring that the Control and CHO groups' diets were isocaloric during the inter-trial recovery period. Performance and "split" times, and the physiological demands on the subjects, were monitored throughout both trials. Whilst no significant difference was found in final 30km time for either group, 8 of the 9 subjects consuming a high carbohydrate diet between trial 1 and trial 2 recorded faster times, although the margin of improvement was small (a mean of 2.6 ± 1.5 minutes). However, analysis of split times revealed that the high carbohydrate group were able to sustain significantly faster running speeds during the final 5km of their second (high carbohydrate) trial ($3.64 \pm 0.24 \text{ m.s}^{-1}$ vs $3.44 \pm 0.26 \text{ m.s}^{-1}$). The data can be extrapolated for the full 42km distance of a marathon, based on the fatigue (decrease in running speed) demonstrated between the 5th and 6th five kilometre splits of the 30km trials, and extending this decrease in speed to include the final 12km. When this data extrapolation is undertaken for the Control group, it predicts a mean marathon time of 204.6mins (3hrs 24mins 36s) for Trial 1, and (3hrs 26mins 18s) for Trial 2, a decrement in Trial 2 of 1min 42s, or 0.8%. However, data extrapolation for the high carbohydrate group suggests a mean marathon time of 199.2mins (3hrs 19mins 12s) for Trial 1, compared with a time of 191.5mins (3hrs 11mins 30s) for Trial 2. This represents an improvement of 7.7min (3.9%) after consumption of a high carbohydrate diet, considerably more than that observed over the shorter 30km distance. The CHO group demonstrated higher blood glucose levels for the final 10 km of Trial 2 compared with Trial 1, and a trend for higher RER values throughout, which was statistically significant at the 5km and 20km points.

When the additional carbohydrate required to achieve the observed improvements in performance is calculated, it suggests that a total of 297g of CHO was used by the CHO group in Trial 1, and 330g in Trial 2. Thus the performance enhancement and reduced fatigue required an additional 33g of CHO, whereas the CHO consumed during the 7 day recovery period was 3476g, an increase of 1138g as a result of the high CHO diet. Clearly the performance enhancement has occurred using only a small fraction of the additional CHO consumption, suggesting that the nutritional advice provided to runners still needs reflection and possible refinement.

4.1.4 Publications 4, 5, 9 and 10:

The following two papers and Book Chapters form part of a linked set of publications gaining greater insight into the demands of women's soccer, and the consequent nutritional demands that soccer places on female players

Davis J.A. and Brewer J. (1993) Applied physiology of female soccer players. Sports Med. 16(3): 180-189

Brewer J. (1994) Nutritional aspects of women's soccer. J Sports Sci. 12 Special No: S35-38

Book Chapters.

Brewer J. The Female Player. (1994) In: Football (Soccer) Ed. B Ekblom, Pubs: IOC Medical Commission

Brewer J. Nutrition for team sports (1995). In: Sports Nutrition for Women. Authors: Bean, A., and Wellington, P. Pubs A&C Black, London

Aim

Having established a relationship between nutrition and endurance performance, these papers and book chapters were written at the request of the Football Association. These are review papers, which collate the latest research in women's soccer. At the time, there was a paucity of research into the sport, and little was known about the demands upon players, and the nutritional interventions that would be required to support training and

competition. The Football Association commissioned this work to get a better understanding of the demands of female soccer, the physiological characteristics of players, and the optimal nutritional interventions to support match-play and training.

Contribution to the advancement of knowledge.

These publications helped to establish a greater understanding of the demands of female soccer, and highlighted the physiological factors that influenced performance. Prior to this, there was some reluctance to associate high carbohydrate diets with team sports, with high protein diets still prevalent prior to competitions. The Davis and Brewer (1993) paper was the first to establish the physiological demands faced by female players, and their physiological characteristics. As a consequence of this paper, the invited Brewer (1994) paper, reviewing the nutritional demands of female soccer, was part of a wider Consensus Conference commissioned by FIFA, the International Governing Body for soccer, and formed an integral part of the recommendations made by FIFA for nutritional practices in soccer. The author presented to an invited audience at this Consensus Conference, and was subsequently invited by FIFA to publish the submitted paper in the *Journal of Sports Sciences*. It was the first paper of its kind to focus on the nutritional demands of female soccer, with clear recommendations on the dietary regimens and practices that should be used to support training and competition.

In 1994, the International Olympic Committee's, (IOC) Medical Commission, invited selected authors to submit applied papers for publication in the *IOC Handbook of Sports Medicine and Science: Football (Soccer)*. The submitted book chapter, *The Female Player*, was written for this prestigious publication and built upon the previous research

papers exploring the physical and nutritional demands of female soccer. The "Nutrition for Team Sports" chapter, published in 1995, made general recommendations on the nutritional needs of female team sports players, and was unique in its focus on advice for females.

Findings

The overall finding of these publications was that the demands of female soccer place an energy requirement on females that requires appropriate nutritional strategies to support both match-play and training. The mean VO_2 max sustained by female players was close to 70%, with intermittent high intensity exercise, mainly in the form of short sprints, increasing the rate of muscle glycogen. These studies concluded that female soccer players should be encouraged to consume a diet that is high in carbohydrate on a daily basis, but modified during periods of the year when the training and playing demands may be reduced, such as the close season. The studies highlighted the potential issue of reduced energy intake amongst some female players concerned about weight management, and as a result concluded that a CHO intake target based on a "grammes per kilogramme of body weight per day" may be more appropriate than a simple percentage of daily energy intake. It was concluded that a minimum of 6g of CHO per kilogramme of body weight per day should be recommended to female players, and that those working with them should be aware of the potential risk of eating disorders. It was also concluded that whilst vitamin supplementation should not be necessary if a female player is consuming a diet of appropriate quality and variety, female players should be encouraged to consume foods that are high in calcium and iron, or if necessary provided with suitable supplements.

These publications highlighted the link between nutrition and team sport performance. Whilst accepting that this link is not as well defined as in endurance activities, they confirmed that studies such as Publication 3, which demonstrate a link between nutrition and work rate, can be applied to team sports where high work rates are required throughout a match. Furthermore, studies demonstrating the impact of nutrition on recovery can also be applied to team sports, where recovery from regular training is essential if match-day performance is to be optimised. Finally, the publications recognised the conflicting demands of many female players not in full time training who have to combine work with sport. Consequently the need for frequent, small volume high CHO meals was highlighted as a means of ensuring that sufficient CHO is consumed to support training, recovery, and competition.

4.1.5 Publications 6 and 8

Brewer J (2011) Low calorie sweetness and hydration: applications in exercise and sport.

Journal of AgroFood Industry 22(5) 35-38

Needleman et al (2014) Consensus Statement on Sports Drinks and Oral Healthcare,

British Journal of Sports Medicine. (In press).

Aim

The aim of the Brewer (2011) paper was to explore the use of artificial sweeteners in the manufacture of sports drinks designed to enhance sports performance, through the replacement of fluid and carbohydrate. It was based on a keynote presentation at the Annual Conference of the International Sweeteners Association in Brussels in 2012. The presentation and paper resulted in an invitation to contribute to the Needleman et al (2014) Consensus Statement, which confirmed the role of artificial sweeteners in sports drinks, specifically with regard to their role in reducing tooth decay by enabling the sugar content to be reduced, whilst maintaining the required osmolality of hypotonic and isotonic drinks.

Contribution to the advancement of knowledge

The Brewer (2011) paper provides an overview of the way in which artificial sweeteners can be used to support the science-based formulations that are required to optimise the absorption of fluid and CHO during exercise. The paper provides the first insight to the role that sweeteners play in regulating the calorific content of a drink, its osmolality, and taste, so that science-based formulations can be achieved when developing effective, palatable products. The paper helped to confirm that the use of artificial sweeteners in sports drinks can be used to restrict calorie intake for those who exercise to lose weight, to sustain the

science-based formulations that are required to optimise hydration, reduce the risk of dental erosion, whilst ensuring that products retain a taste that encourages consumption. The use of artificial sweeteners to reduce the sugar content of a sports drink is also likely to reduce the risk of tooth decay and erosion, and this resulted in an invitation to contribute to the Needleman et al (2014) Consensus Statement on Oral Healthcare and Elite Sport Performance. This paper is the first time that guidelines on oral healthcare have been provided for both manufacturers and users of sport drinks, and is likely to have a significant impact on the industry and consumer awareness.

Findings

The Brewer (2011) paper is the only one of its kind to explore and justify the role of artificial sweeteners in the manufacture of sports drinks. It identifies the need for consumption of appropriately formulated sports drinks to sustain performance. Critical to this formulation is the osmolality of a drink (the number of particles per kilogramme of solvent), which in the case of a sports drink designed for rehydration and refuelling, consists primarily of sodium and carbohydrate. In products designed to optimise hydration, (hypotonic solutions), the paper concluded that many manufacturers use artificial sweeteners to achieve the required low osmolality whilst maintaining palatability. In isotonic beverages, where a higher concentration (above 4%) of carbohydrate is needed to optimise energy absorption, artificial sweeteners provide manufacturers with the flexibility to up-regulate osmolality without compromising taste or increasing the calorific content. The paper concludes that whilst there is some debate about the use of artificial sweeteners in food products, their use in hydration products helps manufacturers produce a range of science-based products that are proven to enhance performance. Without the use of artificial sweeteners, it is likely

that the calorific content and osmolality of a sports drink would increase. Since the majority of sports participants take part in activities where dehydration may be a greater challenge than glycogen depletion, formulating drinks that optimise fluid absorption without providing excessive calories seems a sensible priority.

The Needleman et al (2014) Consensus Statement on Oral Healthcare and Elite Sport Performance highlighted the impact of sports drinks on dental erosion and dental caries. The contribution from the author to the Consensus Statement focussed on the role of a drink's sugar content and pH, and how good practice by both manufacturers and athletes can help to mitigate the challenge of sports drinks to oral healthcare. The specific exercise modalities where sports drinks are required were identified, together with the role that artificial sweeteners play in sustaining taste and reducing sugar content.

4.1.6 Publication 7

Brewer J. and Warren L. (2014). A review of the potential implications of hot and humid environmental conditions on soccer match play performance. *International Journal of Sciences: Basic and Applied Research*. Vol 15(1) 584-589

Aim

This paper was commissioned by Lucozade Ribena Suntory Ltd., to support the marketing and educational activities for the Lucozade Sport carbohydrate-electrolyte drink during the 2014 soccer World Cup. The aim was to assess the impact of climatic conditions that players would experience in Brazil (and in particular the tropical conditions at one of the venues), and to gain an understanding of how this would impact on their performance. The paper also reviewed and recommended strategies that could be adopted to cope with these conditions.

Contribution to advancement of knowledge.

This paper played a significant part in raising awareness of the impact of hot and humid conditions on soccer performance, and the strategies that can be adopted to manage the thermal stress that such conditions place on players. As the largest sports drink brand in the UK, and the Official Sports Drink of the England football team, in 2014 Lucozade Sport activated a £2 million campaign to raise awareness of the role that carbohydrate-electrolyte solutions play in sustaining soccer performance. This paper underpinned the educational and promotional material that was produced for this campaign. This supported the development of an indoor soccer pitch with an adjacent sport science laboratory, where

temperatures of over 30°C, and 75% relative humidity, could be replicated, with players' continuously monitored for work rate and hydration status during matches. Videos and on-line educational content were developed, with comments on the findings from this paper on (amongst others), BBC Breakfast TV, ITN News, Channel 4 News, Radio 5 Live (twice), the Times, Telegraph, Metro, Daily Mail and Sun newspapers, plus numerous on-line news sites.

Findings

The paper reviewed a series of publications assessing the impact of hot and humid conditions on soccer performance and thermoregulation. It concluded that a number of factors would be impaired, including work rate, fatigue, cognition and recovery. This is likely to result from the high thermal stress caused by the combination of heat and humidity affecting the body's ability to sustain thermal equilibrium. Sweat rates of approximately 3 litres per hour could be encountered, resulting in dehydration and loss of electrolytes. Whilst this could be partially alleviated by the use of carbohydrate-electrolyte solutions, it is likely that most players will suffer some degree of performance degradation, especially during the latter stage of a match. As a result, match-play tactics should be adapted and players must pay particular attention to their post-match recovery and rehydration strategies. The paper concluded that whilst glycogen depletion may be an issue towards the end of a match, this is less likely to be a performance-inhibiting factor than dehydration and thermal stress.

4.1.7 Publication 11 (Book)

London 2012 Guide Athletics – Track Events, Carlton Books. Author J Brewer. Published 2011. ISBN 9781847326980

Note

This Official London 2012 Training Guide for Athletics (track) was commissioned by LOCOG as part of a small series of sports-specific publications for the London 2012 Olympic Games. J Brewer is the sole author of the book, with specific sections and chapters relating to sports science, sports nutrition and hydration. It targets both elite and recreational athletes. Prior to publication, it was reviewed and edited by LOCOG, and staff from UK Athletics, the national governing body for athletics in the United Kingdom.

Aim

To provide a user-friendly guide to taking part in track athletics, with information benefiting both beginners and serious athletes.

Contribution to knowledge

This book used scientific research, and good coaching practice, to inform athletes and the general public about the sport of athletics, and included advice on sports nutrition and hydration, relating them to both competition and training.

Summary

The book contains specific chapters on "Diet", "Hydration" and "Drugs in Sport", all of which focus on the importance of sports nutrition for athletics. More specifically, the chapter on

"Marathon techniques and training" highlights the importance of energy and fluid replacement before, during and after a marathon, and the chapter entitled "Race Day" provides specific nutrition and hydration advice for the day of a race. These chapters are written with the general public in mind, so whilst not scientific texts, they do provide user-friendly information and advice that is underpinned by science.

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Appendix 1

Other related scholarly activity

As Director of Sports Science for GSK I was responsible for educational material distributed to athletes from a range of sports on sports nutrition and hydration. Of particular note is work supporting both the London Marathon and Great North Run. The London Marathon support includes annual presentations, (for five years), at the pre-race "Meet the Experts" conference, and Runners' Workshops on hydration and nutrition, held during the four days preceding the race.

I have presented invited keynote lectures on sports nutrition and hydration both internationally and domestically. Selected recent examples include:

- **Annual Conference of the International Sweeteners Association** (Brussels, 2011). "Low calorie sweeteners and hydration; applications in exercise and sport".
- **The International Convention on Science, Education and Medicine in Sport** (ICSEMIS, Glasgow 2012) "Practical hydration strategies for active individuals".
- **The British Specialist Nutrition Association's Annual Lecture** (London 2013). "The evolution of sports nutrition: from Ancient Greece, to London 2012 and beyond".
- **Royal Society of Medicine Invited Keynote Lecture** (2014). "Physiological differences between elite and recreational athletes".
- **Sport and Exercise Nutrition Register Keynote Lecture** (2014). "Anti-Doping in sport; challenges, threats and reactions".

As a Government appointed Board Member of UK Anti-Doping, I play an on-going role in anti-doping in sport, with particular emphasis on sports supplements, and quality assurance processes to ensure that they are free of substances banned by WADA.

I am frequently used by the media for quotes and expert comment on matters relating to sports nutrition and hydration, most recently and notably surrounding the demands of playing soccer in the heat of the summer in Qatar.

Appendix 2

Other Peer Reviewed publications.

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Appendix 3

Submitted publications